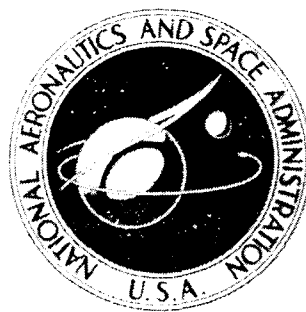


**NASA TECHNICAL
MEMORANDUM**



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**CORRELATION OF TOTAL, DIFFUSE,
AND DIRECT SOLAR RADIATION**

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Cleveland, Ohio 44135

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16. Abstract <p>Present requirements for realistic solar energy system evaluations necessitate a comprehensive body of solar-radiation data. The data should include both diffuse and direct solar radiation as well as their total on an hourly (or shorter) basis. In general, however, only the total solar radiation values have been recorded. This report presents a correlation that relates the diffuse component of an hourly total solar radiation value to the total radiation ratio of the maximum value attainable. The data used were taken at the Blue Hill Observatory in Milton, Massachusetts, for the period 1952 through 1956. The relation - in the form of the data plots - can be used in situations in which only the hourly total radiation data are available but the diffuse component is desired.</p>					
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CORRELATION OF TOTAL, DIFFUSE, AND DIRECT SOLAR RADIATION

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SUMMARY

Present requirements for realistic solar energy system evaluations necessitate a comprehensive body of solar radiation data. The data desired should include both diffuse and direct solar radiation as well as their total on an hourly (or shorter) basis. Data that come closest to these specifications are those of the National Weather Service with more than 60 data taking stations. Except for a very few, most stations record only the total solar radiation values.

This report presents a correlation of the diffuse component of an hourly total solar radiation value to the total radiation ratio of the maximum value attainable. The data used were those of Blue Hill Observatory in Milton, Massachusetts, for the period 1952 through 1956.

The relation - in form of the data plots - can be used in situations in which only the hourly total radiation data are available, but the diffuse component is desired.

INTRODUCTION

The Sun is the Earth's nondepletable source of energy, radiating energy outward in all directions in space. The normal flux of solar radiation at a mean distance between the Earth and the Sun is the solar constant ($q_{sc} = 81.167 \text{ kJ/min} \cdot \text{m}^2$, ref. 1). Approximately 95 percent of the Sun's energy at sea level is in the range of wavelengths from $\lambda = 0.3$ to 2.7 micrometers. About 2.5 percent of the solar energy is at shorter wavelengths and 2.5 percent is at longer wavelengths. The spectral distribution of solar radiation is shown, according to the method of Thekaekara (ref. 2), in figure 1.

The amount of solar energy that eventually reaches the Earth's surface is at an intensity of between 0 to 62.9 kilojoules per minute per square meter as a result of attenuation by absorption of water vapor, ozone, and carbon dioxide; by reflection of dust and

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water droplets, and by scattering of the air molecules (ref. 3). Some of the Sun's scattered and reflected radiation will finally reach the Earth's surface as diffuse radiation.

The total solar radiation reaching the Earth is usually measured by means of a pyranometer (ref. 4). The total solar radiation is the sum of the direct and diffuse solar radiation. The relative magnitudes of the direct and diffuse components vary from day to day, depending on the condition of the sky and on the angle of the Sun. On a very cloudy day nearly all the solar energy is diffuse, whereas on a cloudless day, the diffuse component will be around 10 percent of the total. A typical plot of total and diffuse solar radiations on a clear day for June 20, 1952, at the Blue Hill Observatory in Milton, Massachusetts, is shown in figure 2(a).

Because of the rotation of the Earth, solar energy striking a given spot on the Earth's surface varies in a 24 hour cycle, being essentially zero during the night and increasing in the morning hours as the sun rises. Passing clouds can cause a large and rapid change in the solar intensity. A plot of total and diffuse solar radiations on a partially cloudy day (June 7, 1952) at the observatory is shown in figure 2(b).

Methods for prediction of solar radiation has been developed primarily for clear skies. The papers by Moon (ref. 5), Klein (ref. 6), Threlkeld and Jordan (ref. 7), and Parmelee (ref. 8) discuss the method of prediction. Recent work by Sharma and Pal (ref. 9) has introduced the concept of "clearness number," defined as the ratio of measured direct solar radiation to the computed standard atmosphere solar radiation for the same altitude. Based on this concept, they have developed empirical formulas for calculating direct and diffuse solar radiation on horizontal surfaces from measured total radiation values. Budyko, et al. (ref. 10), developed a formula for relating total radiation on a cloudy day to that on a clear day. The formula depends on the transmittance of clouds for totally covered sky and on the mean amount of cloud for partially covered sky. Norris (ref. 11) attempted to correlate solar radiation with cloud cover and concluded that it is impossible to use cloud information to predict solar radiation because of the doubtful extent of the amount of reduction in the intensity of transmitted radiation and because of the possible increase by reflection of solar radiation reaching the Earth's surface. Liu and Jordan (ref. 12) made a study of solar radiation data from Hump Mountain, North Carolina; Blue Hill Observatory; and Minneapolis, Minnesota. The data for Blue Hill were for a 10 year period (1946 to 1956). They obtained a linear relation between diffuse and direct transmission coefficient for a cloudless sky. They have developed a statistical correlation between daily diffuse and daily total radiation on cloudy days. They have also presented curves relating the ratio of hourly diffuse to daily diffuse solar radiation with hours from sunrise to sunset and with hours from solar noon. In this approach the hourly diffuse values are obtained from the daily values.

The present study investigates the relation between the hourly diffuse values and the hourly total values. This approach is based on the availability of hourly total solar radiation data in at least 60 National Weather Service stations in the United States and

Canada. Practically all of the data are total values only. If a relation can be established between diffuse and total radiation with only the total value known, a more precise computation can be performed for those applications where direct and diffuse differences are important.

RESULTS AND DISCUSSION

The hourly diffuse and hourly total solar radiation data from the Blue Hill Observatory in Milton, Massachusetts, for the 5 year period from 1952 through 1956, was used as a basis for obtaining meaningful correlation. Individual hourly data points were used for correlation studies between diffuse and total values. A correlation for long-term averages is also presented.

Empirical Correlation Between Hourly Total and Hourly Diffuse Solar Radiation

Sky conditions are described by various parameters. The National Weather Service describes cloud cover with a cloud cover modifier that varies from 0 to 1. A cloud cover factor of 0 means clear sky, and a cloud cover factor of 1 means overcast.

A plot of the ratio of diffuse-to-total hourly solar radiation as a function of solar altitude with cloud cover factor as a modifying parameter (fig. 3) reveals that no meaningful correlation can be made. Similarly, a plot of the diffuse-to-total ratio of the hourly solar radiation against the total-to-total maximum ratio for a given month, hour, and solar altitude (fig. 4) indicates that solar altitude is not a meaningful parameter. Sharma and Pal (ref. 9) using solar insolation data for New Delhi, India, showed a similar plot which indicated some relation between the ratio of direct-to-total solar radiation, clearness number, and solar altitude (clearness number being the ratio of normal, direct solar radiation at a location to that for a reference atmosphere).

Solar radiation data for the Blue Hill Observatory from 1952 through 1956, have been analyzed, and a correlation plot made of hourly values of diffuse-to-total radiation against hourly values of total to total maximum radiation in figure 5. Total-maximum refers to the highest value of total radiation for the particular hour and month considered over the 5-year period.

The widest scattering of data occurred during November and December, the least during June. A trend in the data is clearly indicated, however. A least squares fit of a cosine function has been drawn through the data points. This function

$\left[y = \alpha + (1 - \alpha) \left(\cos \frac{\pi}{2} x \right)^\beta \right]$ was chosen to incorporate features that would be expected of a curve relating diffuse and total radiation. Expecting that the total radiation would be

entirely diffuse as the total-to-maximum total ratio approaches zero, the curve was fitted to pass through 1 on the ordinate. One other feature incorporated into the function is that of zero slope at the end points. The coefficient and exponential values of the function are tabulated in table I. Cloud cover factor was considered in an attempt to reduce data scatter. No improvement was noted.

The scatter of the data for any one month, generally, is less at the higher total-to-total maximum values. This portion of the curve is also the more useful part for such applications as the solar heating and cooling of buildings. In these applications the mode of operation that collects solar energy must be balanced by energy losses entailed in such operations. Low total radiation could very well result in an overall energy loss for the system.

Long-Term Averages

The parameters used in figures 5, and the shape of the least square curve suggests a similarity to the parameters and curves used by Liu and Jordan in reference 12 (fig. 7 of that reference). In that paper daily values were used as well as calculated extraterrestrial insolation values. Extraterrestrial insolation was investigated in the present report on an hourly basis, but was found to cause more scatter than by using the actual, hourly, total maximum values. Liu and Jordan's use of average radiation values - whether daily or monthly - has enabled them to reduce scatter and consequently make more apparent the relation between diffuse and total solar radiation. It must be realized, though, that the average values were based on essentially the same scattered data as presented in figure 5.

Using a similar approach to that of Liu and Jordan, the hourly total solar radiation data points were grouped according to a particular hour and a particular month over the 5-year period. Each group was then divided into 3.5 kilojoule-per-minute-per-square-meter intervals. The data points within each interval were then averaged. For each total radiation datum, there is a corresponding diffuse point. These diffuse data points were averaged. It is these individually averaged values that form the ratios of diffuse-to-total (average) and total-to-total-maximum (average) used in figure 6.

The points in these figures do form a clearer relation of hourly diffuse and total radiation. The point scatter is more extensive than Liu and Jordan's, as may be expected from using smaller time increments, even though it is averaged. More importantly, the trend of these averaged points emphasizes the similarity to Liu and Jordan's averaged points and further validates the curves drawn through the data points in figure 5.

CONCLUSIONS

A present concern in designing solar energy systems is the need for continuously measured, total, diffuse and direct solar radiation data. Only by simulating the time-increment by time-increment weather variations in a system based on actual data can a realistic evaluation of the system be obtained. The climatic records in this country and Canada include hourly total solar radiation for more than 60 locations. Only at a very few stations is the diffuse component of the total solar radiation - a matter of significance in the design of solar collection systems - measured.

At one such station, the Blue Hill Observatory, in Milton, Massachusetts, diffuse as well as total hourly solar radiation data were taken over a 5-year period. In the study reported here, a correlation of Blue Hill data was made using two ratios. The abscissa was of the hourly total radiation as a ratio of the maximum value obtainable for that hour over a 1 month period. The ordinate was the hourly diffuse solar radiation as a ratio of the hourly total radiation.

The plotted data indicated varying degrees of scatter - more pronounced during the winter months, less so during summer. In all cases the scatter was much less pronounced where the total radiation approached the maximum total radiation value - the region where diffuse and direct radiation would be most significant for a solar energy system design.

The method described herein and plotted data indicate the relation of the diffuse component to the total radiation value. It can be used in situations where only the total radiation values are known but the diffuse component is desired.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 16, 1976,
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TABLE I. - CURVE-FITTING VALUES

SOLAR RADIATION DATA

$$\left[y = \alpha + (1 - \alpha) \left(\cos \frac{\pi}{2} x \right)^2 \right]$$

Month	α	β	Month	α	β
January	0.165	2.516	July	0.0508	1.312
February	.124	2.535	August	.0802	1.483
March	.133	1.960	September	.167	2.365
April	.0885	1.744	October	.154	3.716
May	.0840	1.526	November	.224	4.218
June	.0496	1.121	December	.191	1.894

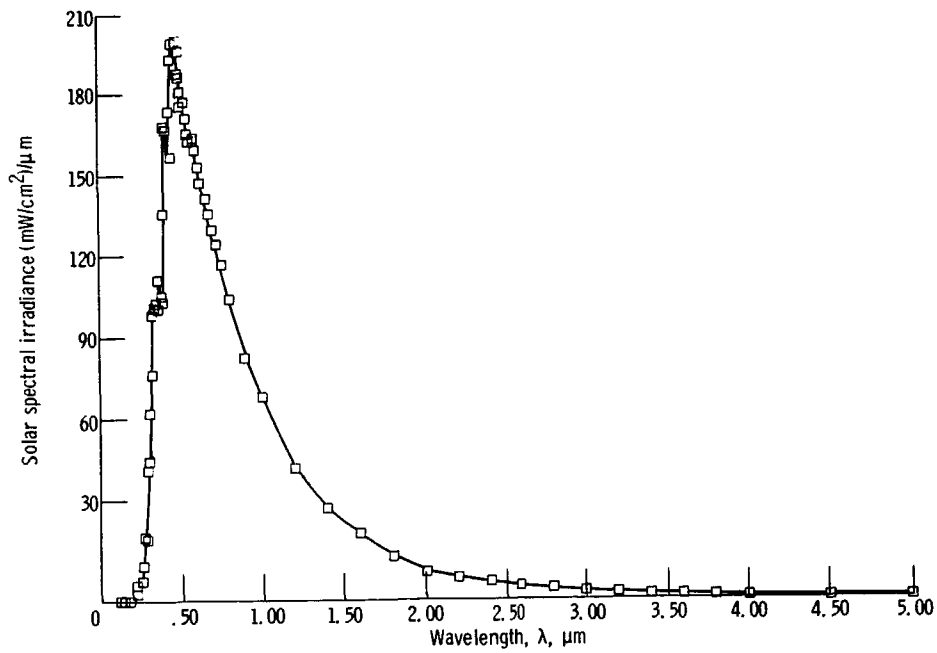
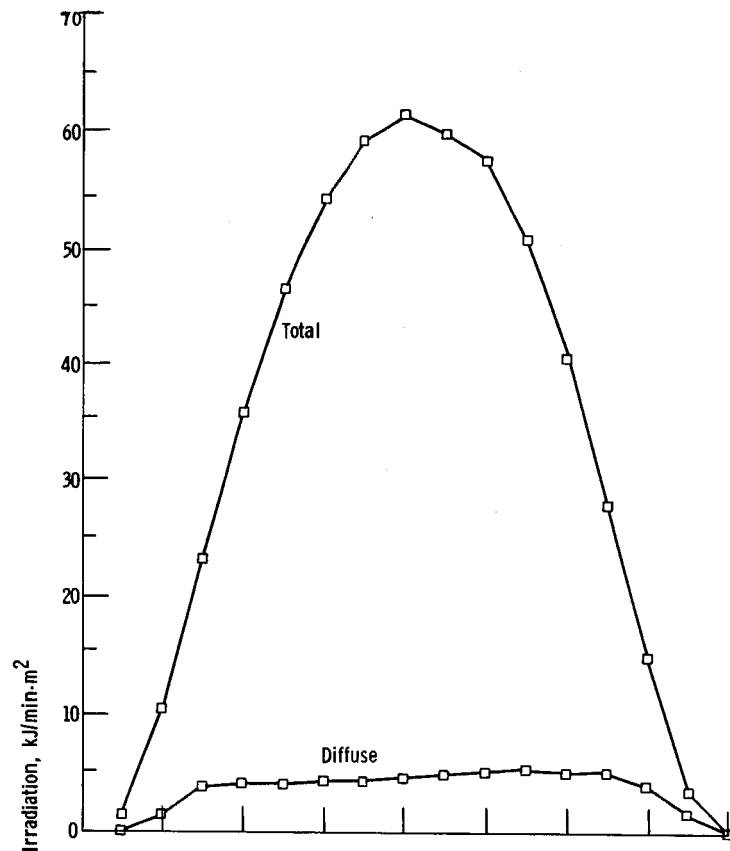
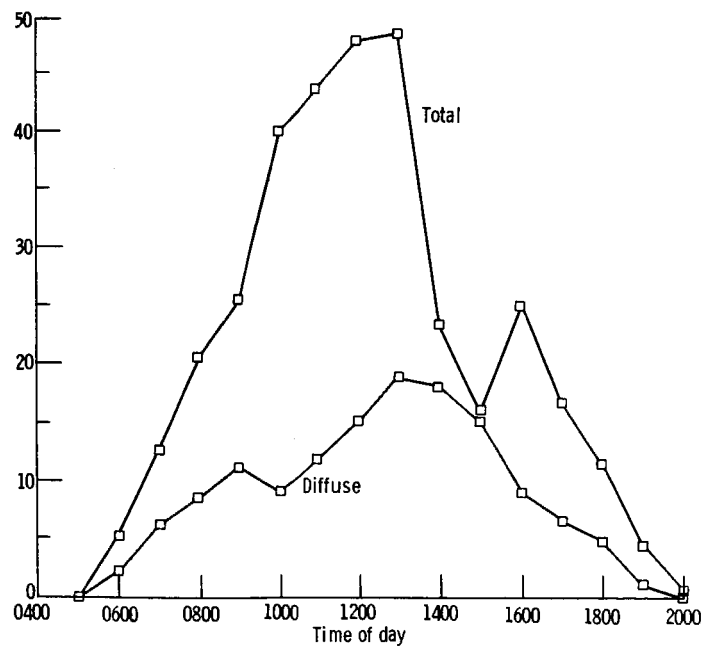


Figure 1. - Spectrum of solar radiation (ref. 2).

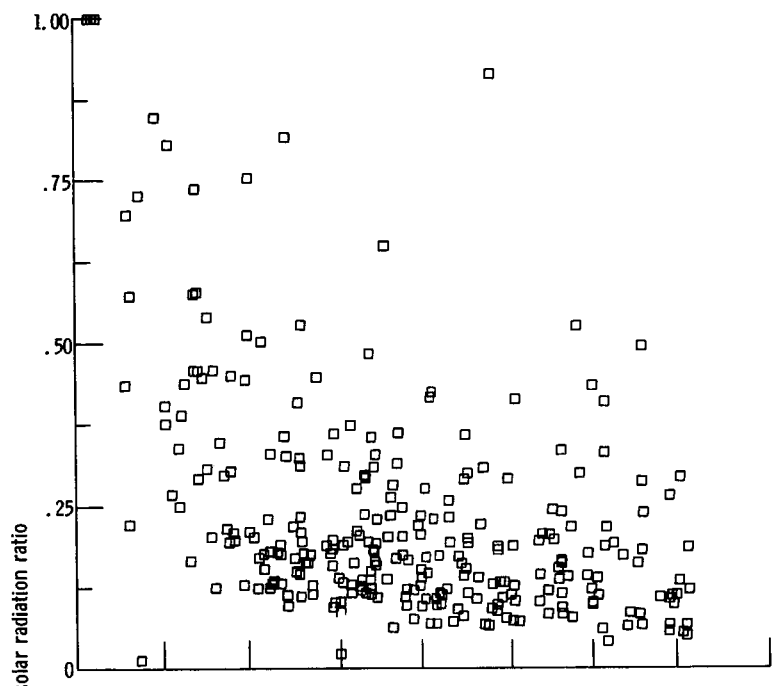


(a) Cloudless day - June 20, 1952.

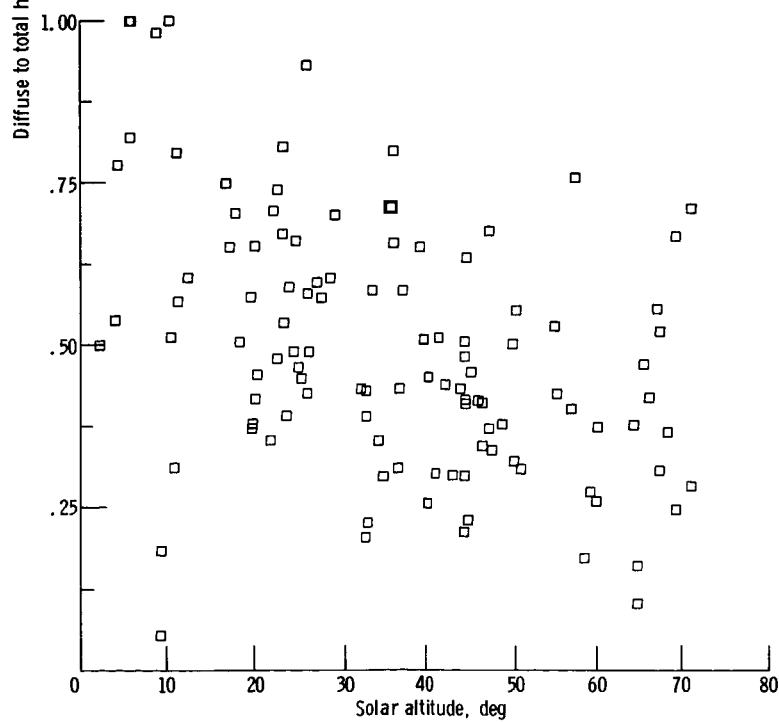


(b) Partially cloudy day - June 7, 1952.

Figure 2. - Typical total and diffuse solar radiation patterns.

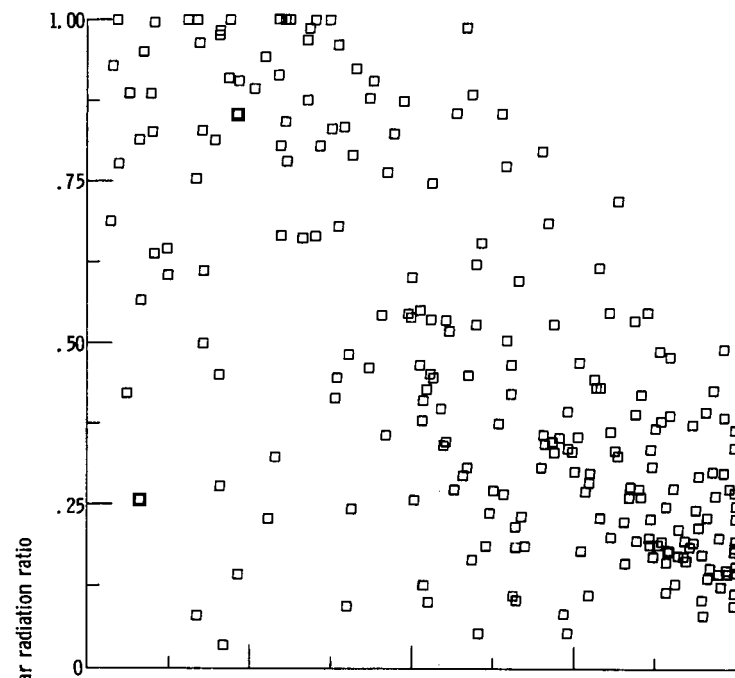


(a) Cloud cover factor, 0.10.

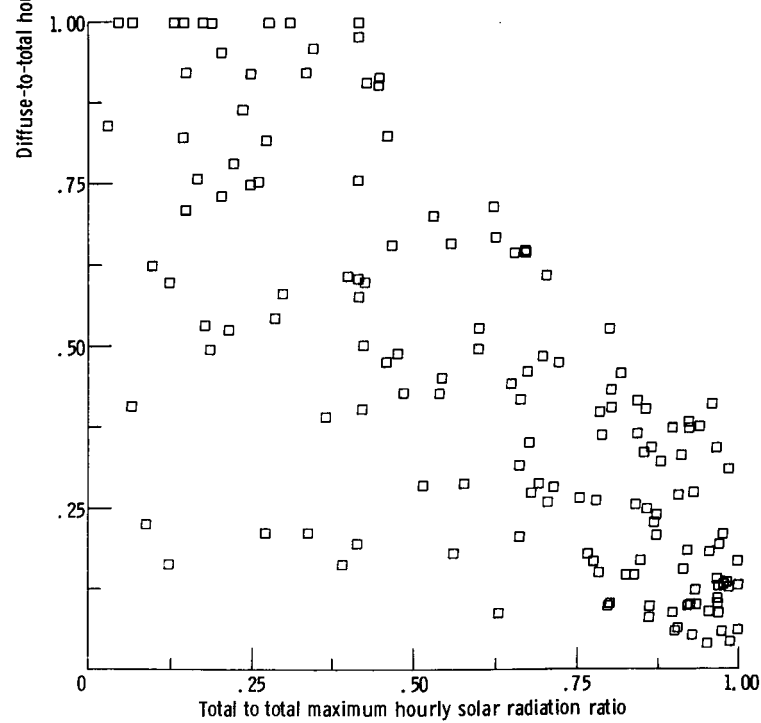


(b) Cloud cover factor, 0.50.

Figure 3. - Diffuse-to-total hourly solar radiation as function of solar altitude.



(a) Solar altitude, 19° to 20°.



(b) Solar altitude, 59° to 60°.

Figure 4. - Diffuse to total hourly solar radiation ratio as function of total to total maximum hourly solar radiation ratio.

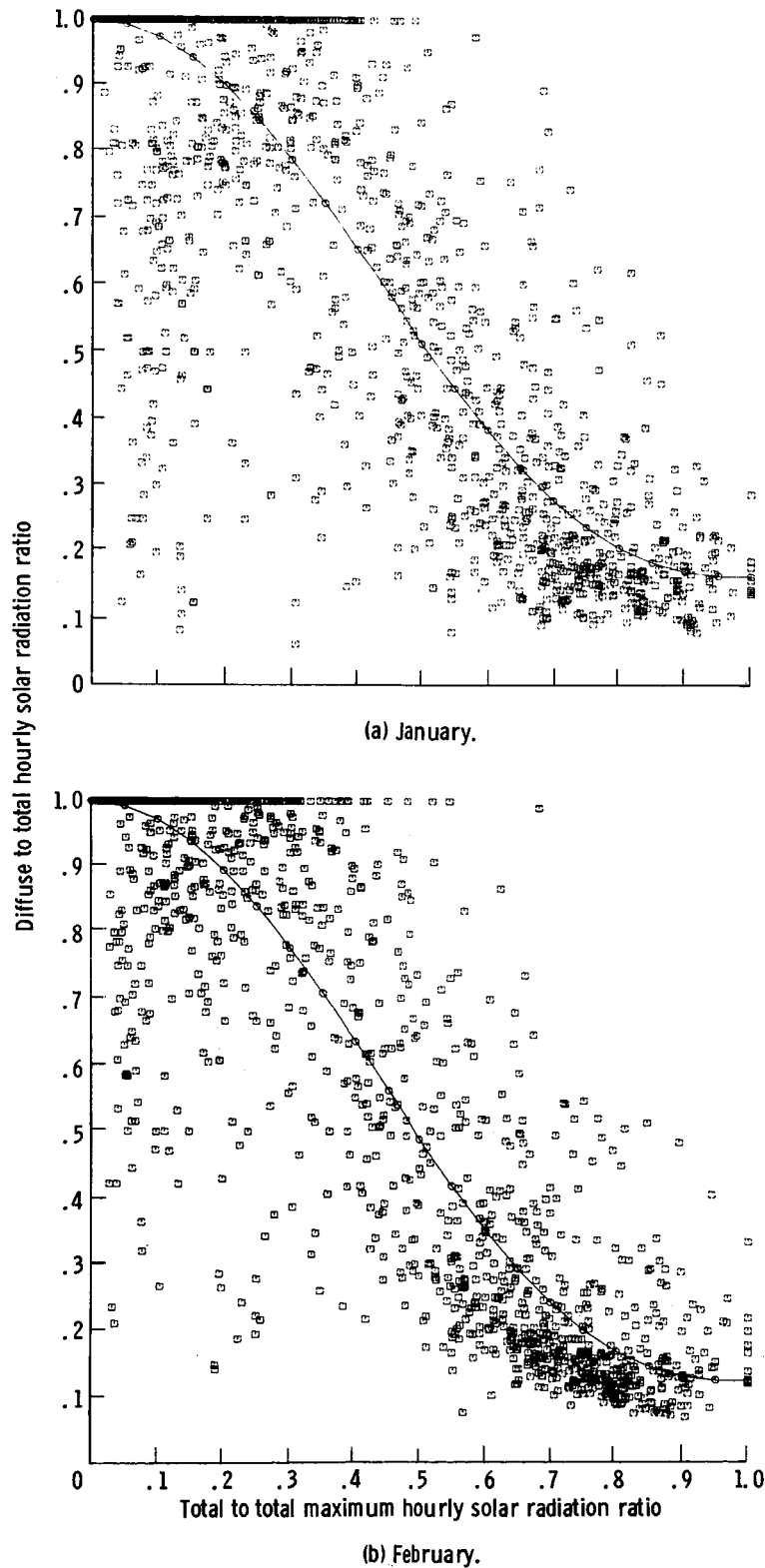


Figure 5. - Correlation of hourly total and diffuse solar radiation. Insolation data from Blue Hill, Massachusetts, for the period 1952-1956.

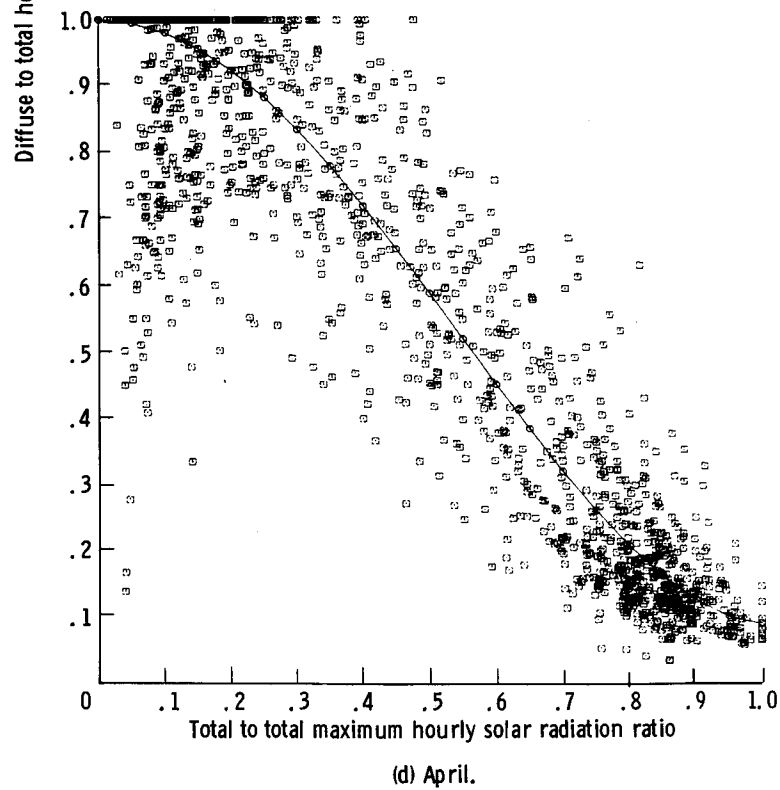
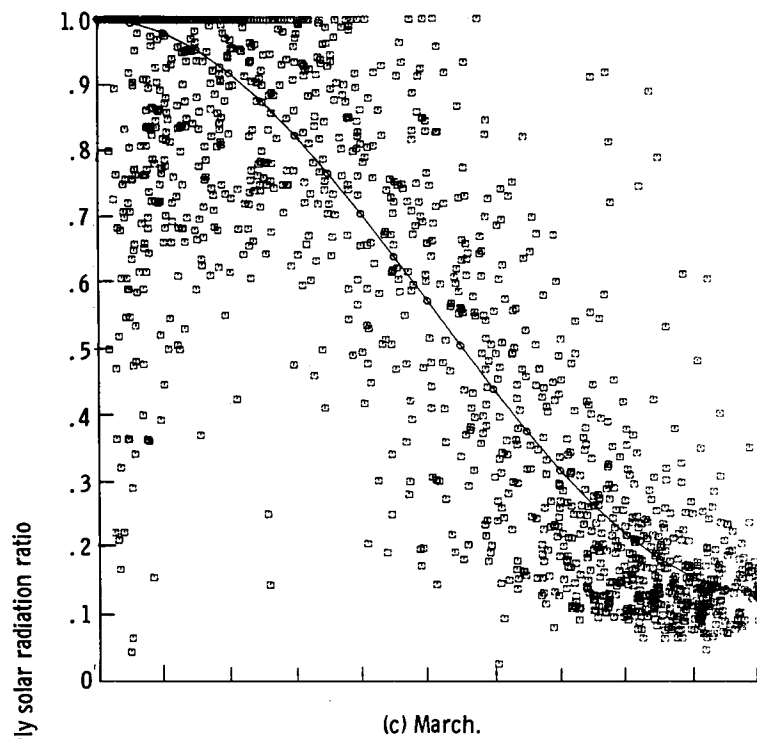
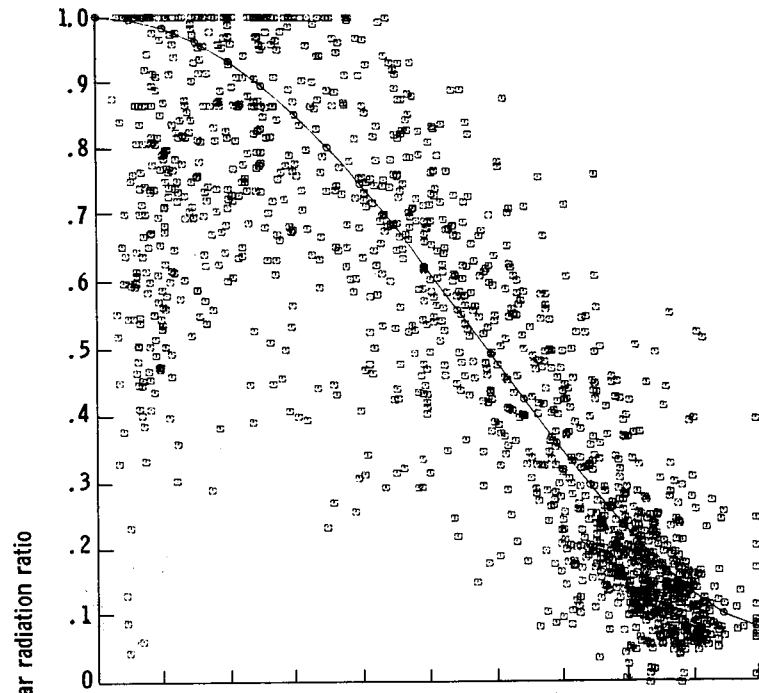
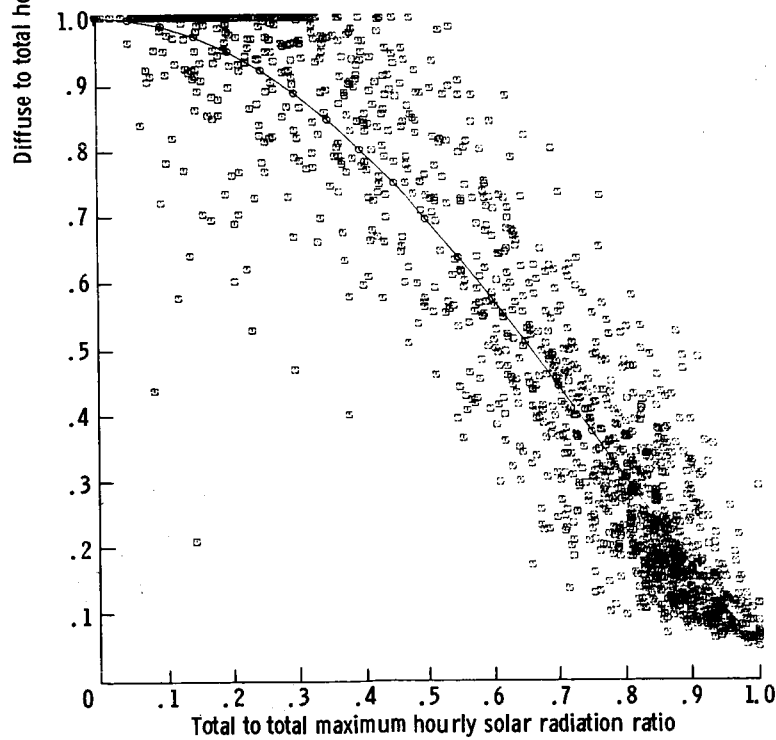


Figure 5. - Continued.



(e) May.



(f) June.

Figure 5. - Continued.

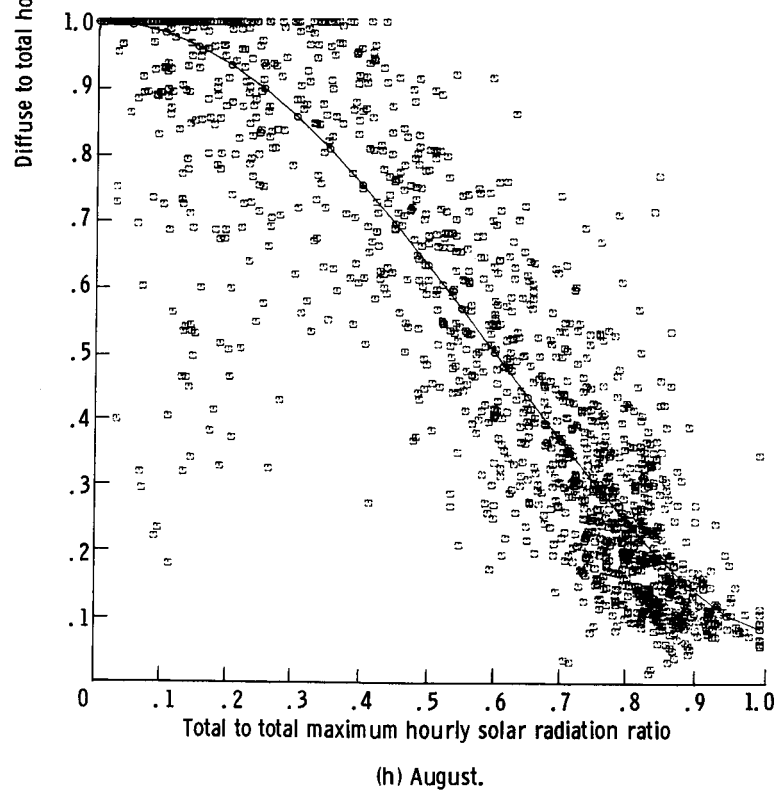
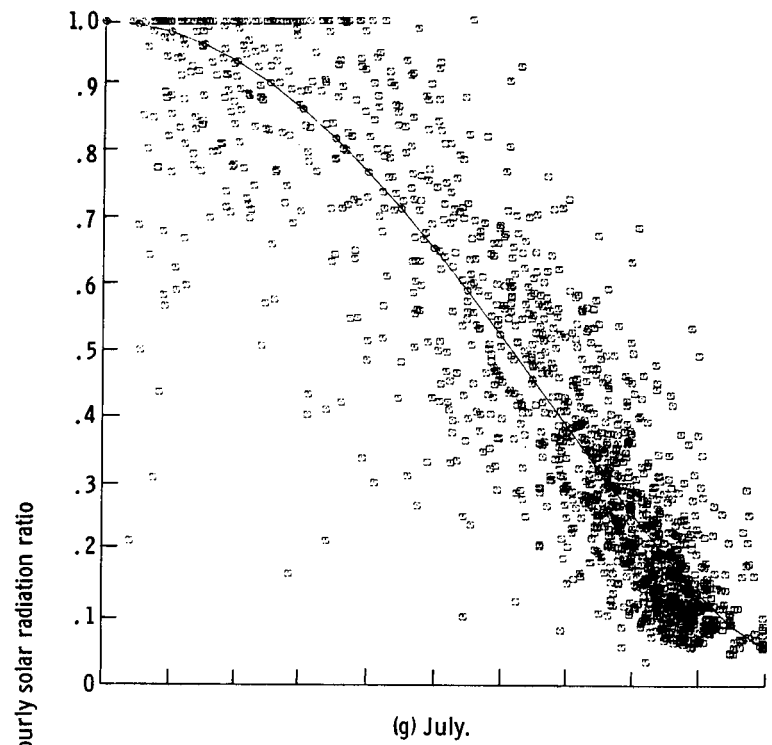


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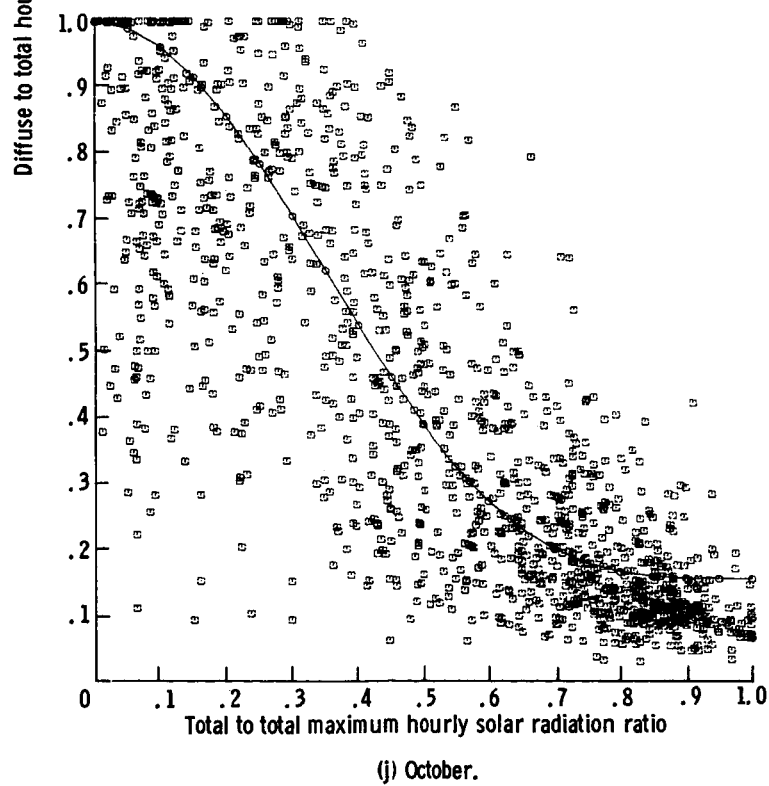
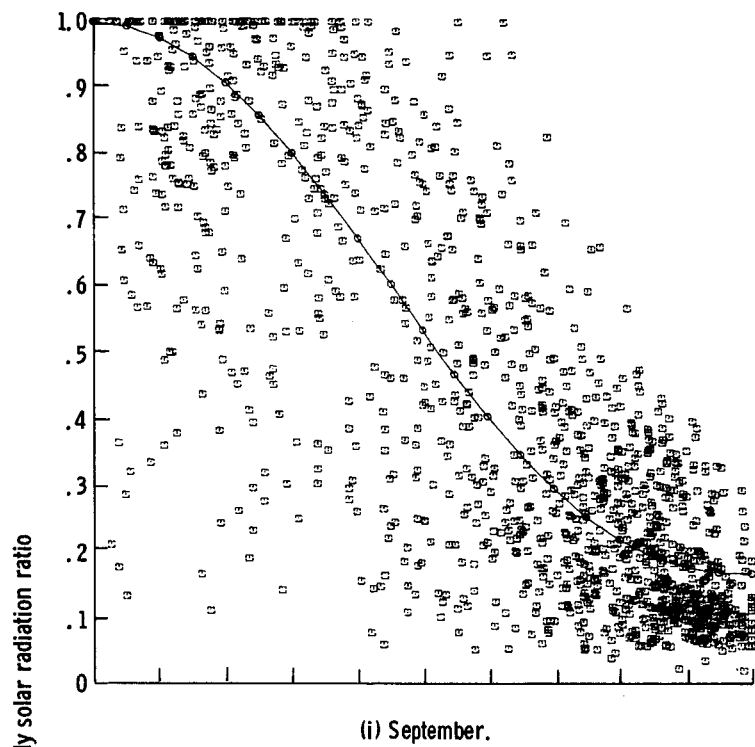


Figure 5. - Continued.

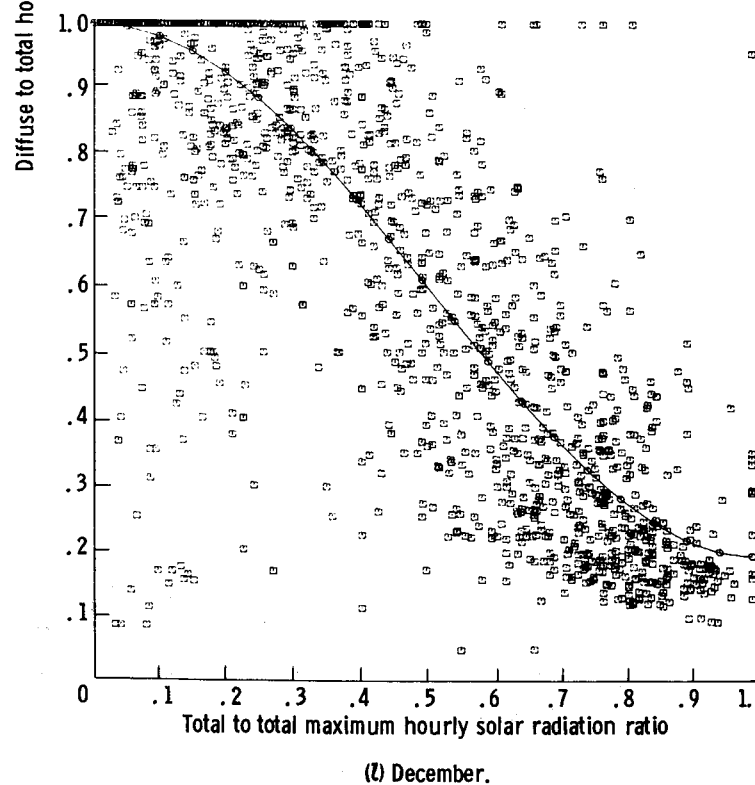
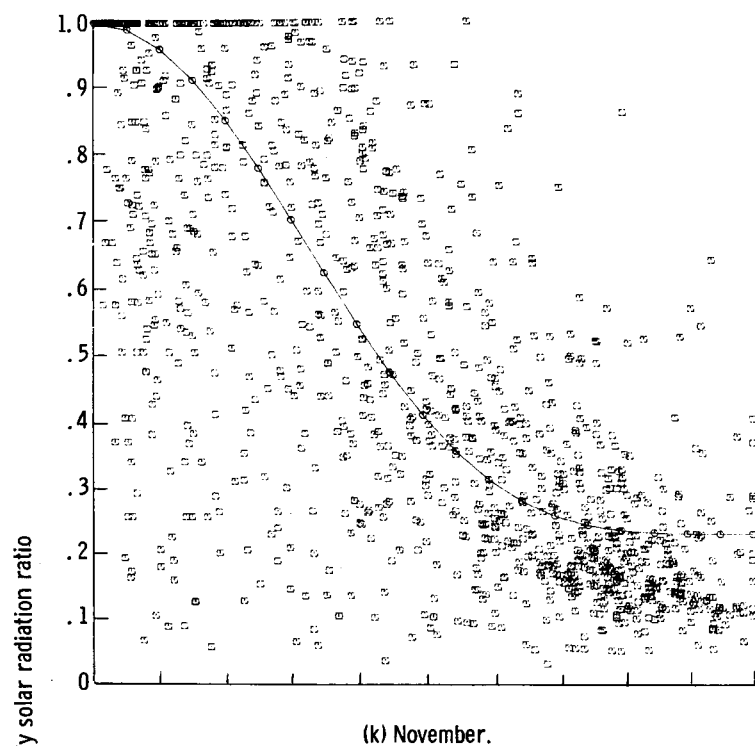


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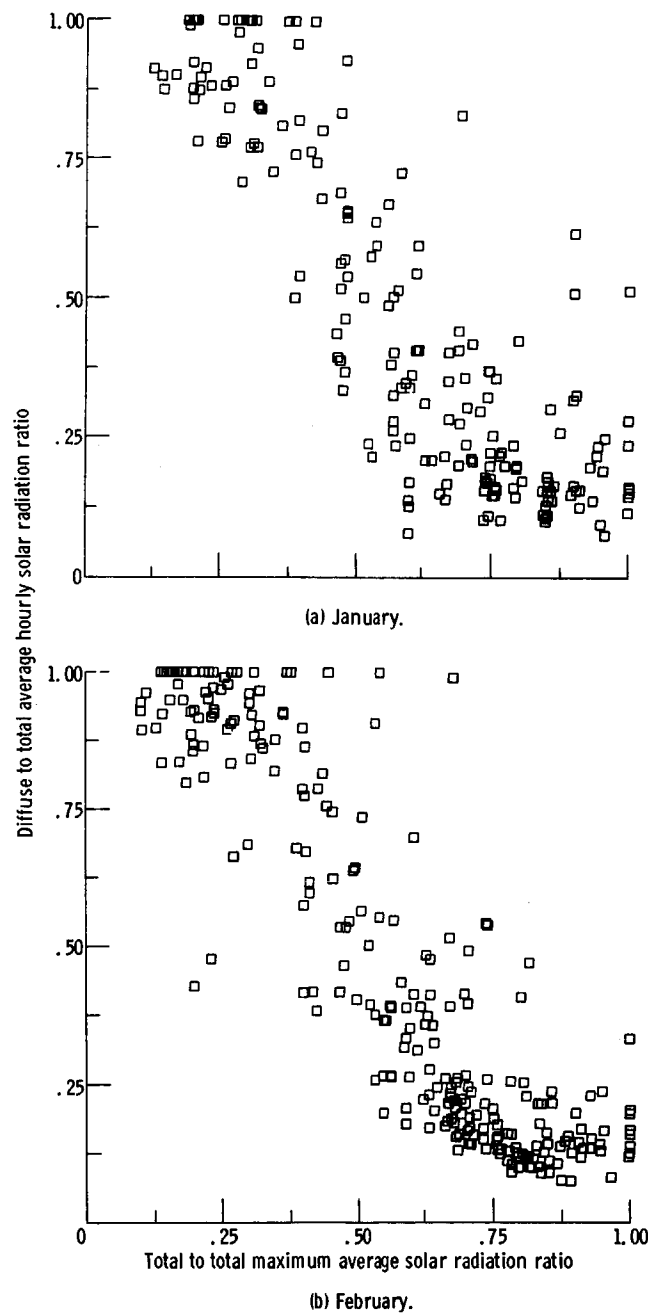


Figure 6. - Correlation of average hourly total and diffuse solar radiation. Insolation data from Blue Hill, Massachusetts, for the period 1952 to 1956.

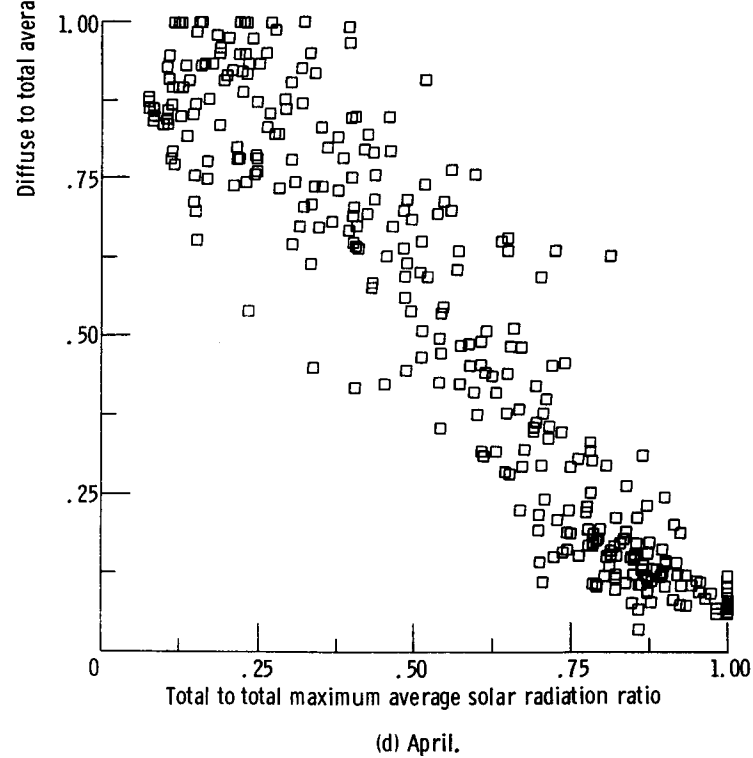
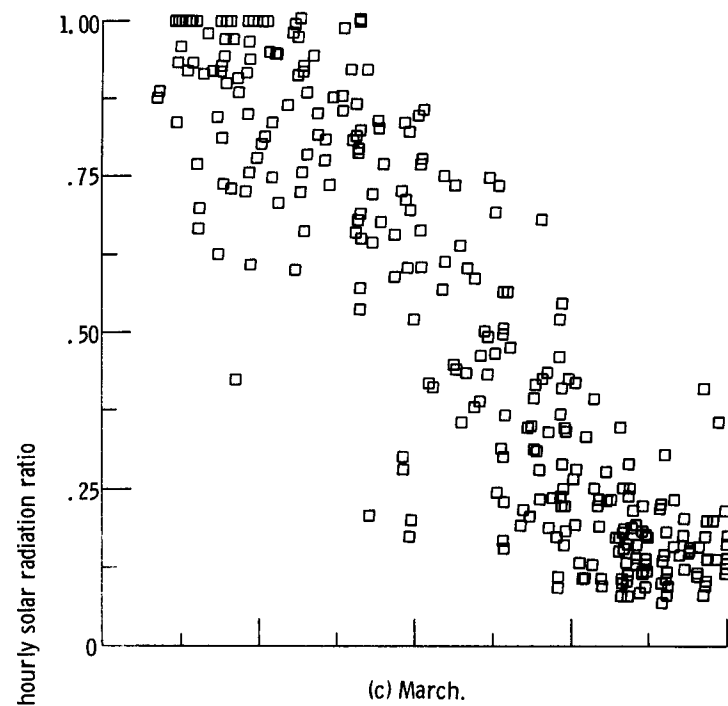
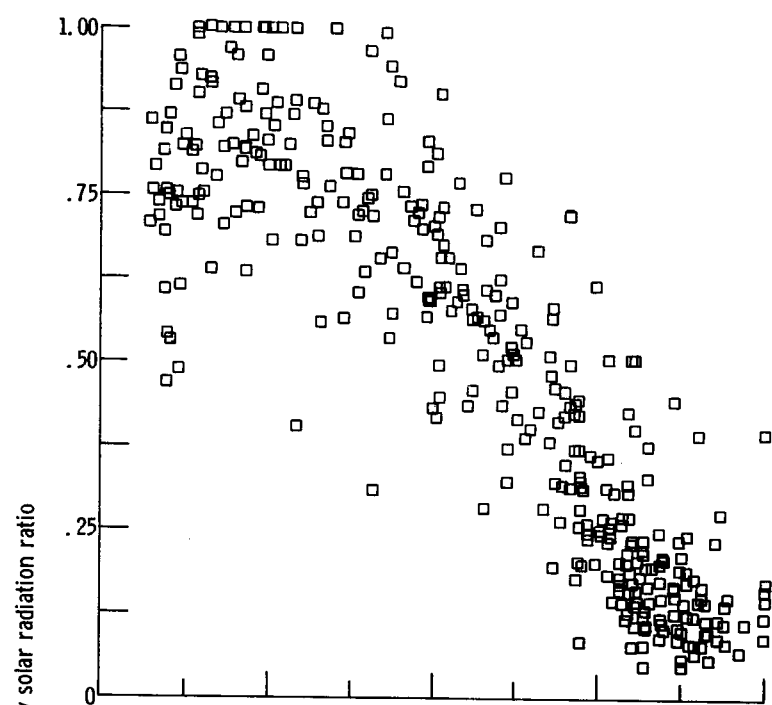
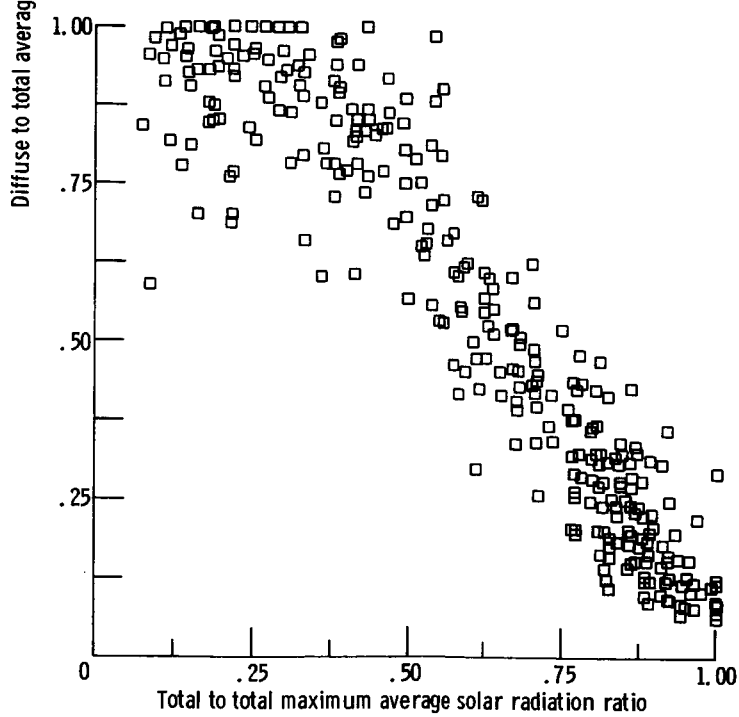


Figure 6. - Continued.



(e) May.



(f) June.

Figure 6. - Continued.

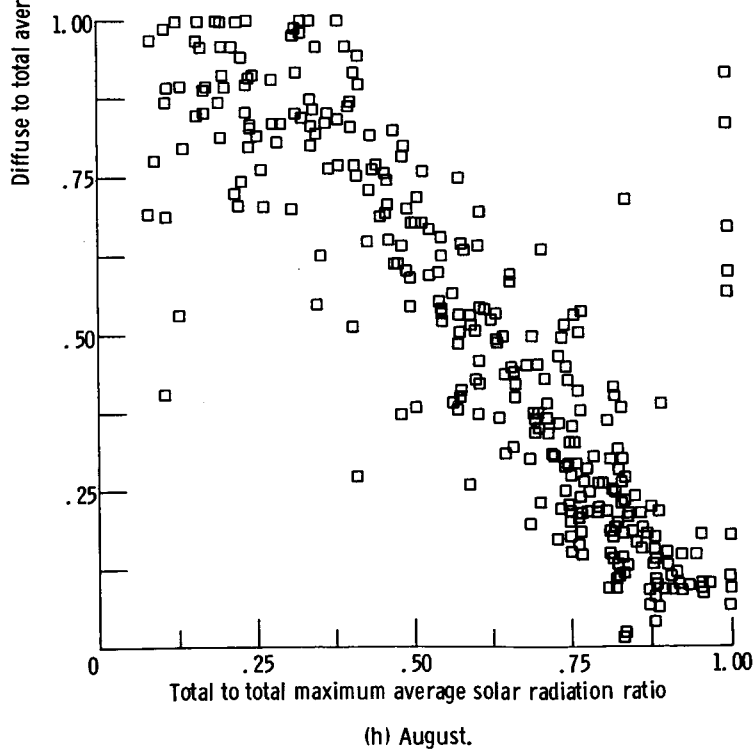
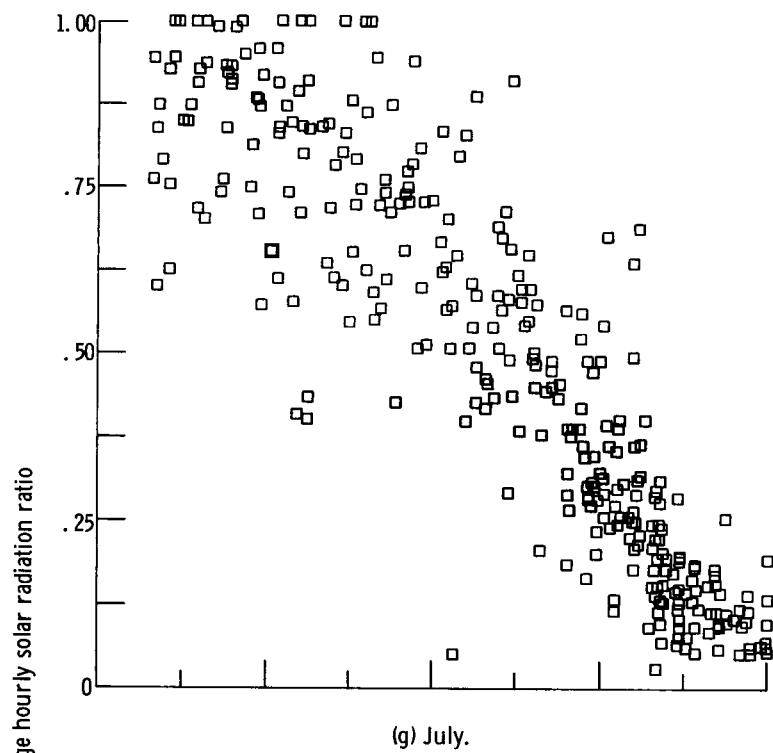


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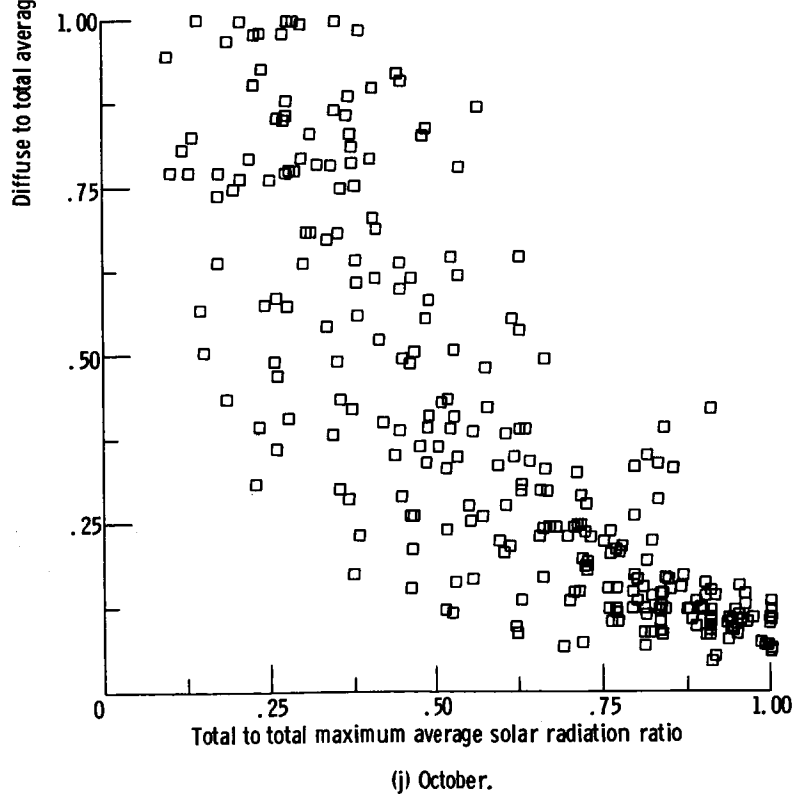
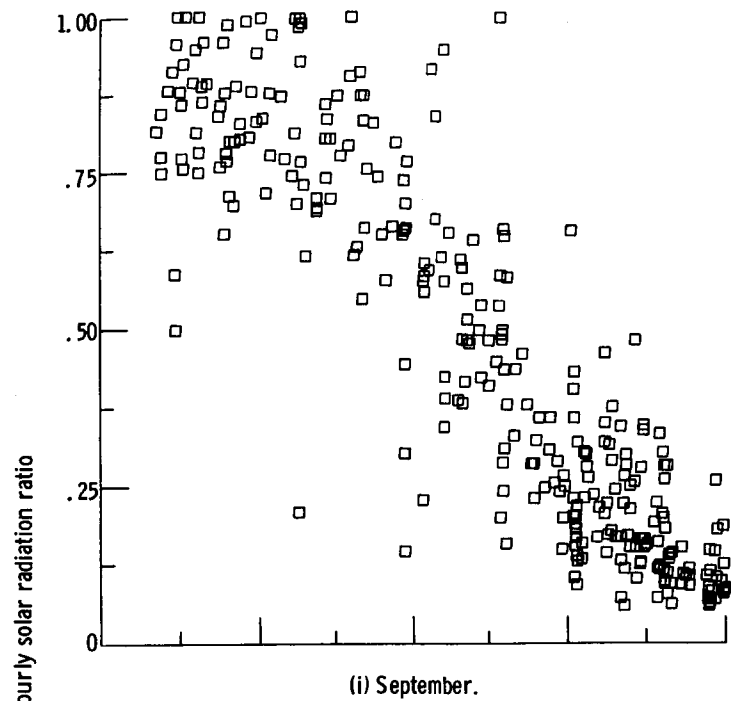
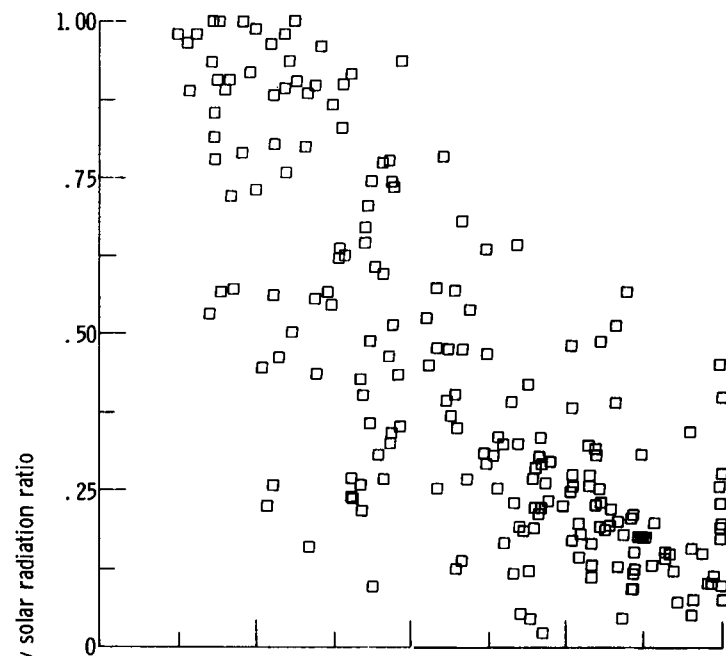
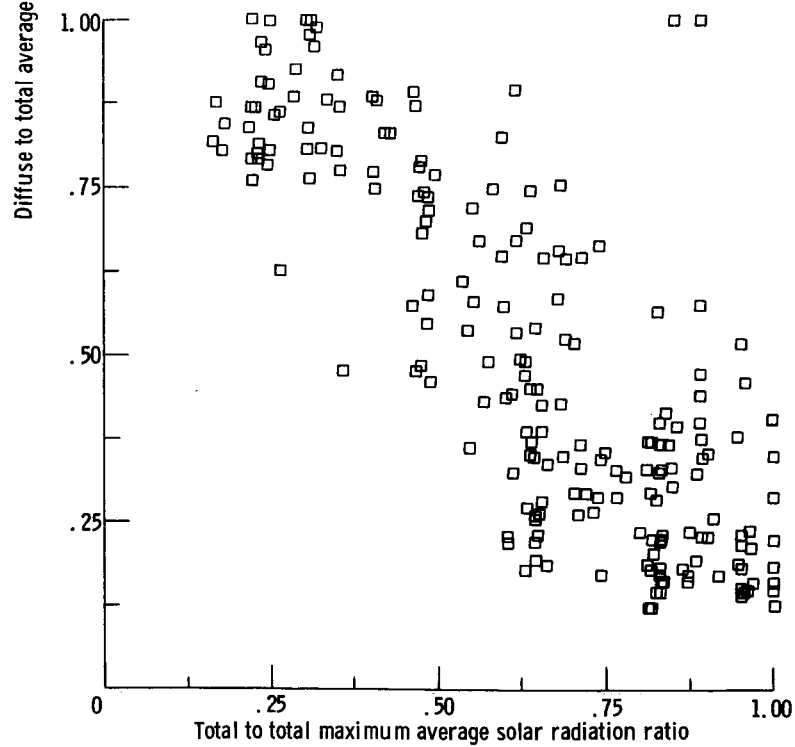


Figure 6. - Continued.



(k) November.



(l) December.

Figure 6. - Concluded.

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ERRATA

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Page 7, table I: The exponent in the equation in the headnote should be β instead of 2.

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